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SEISMIC ATTENUATION TESTS AT THE PORTSMOUTH, OHIO, GASEOUS DIFF--ETC(U)
APR 78 J R CURRO, P F HADALA, G B LANDERS

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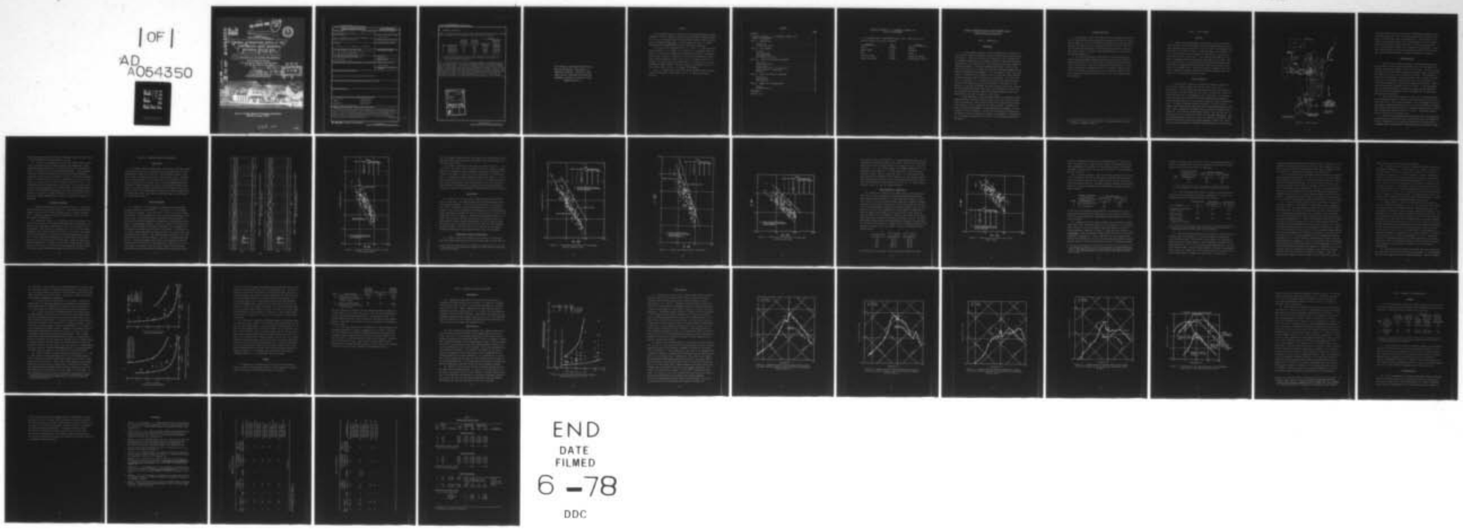

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SEISMIC ATTENUATION TESTS AT THE PORTSMOUTH, OHIO, GASEOUS DIFFUSION ADD-ON SITE

by

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Gaseous Diffusion Add-On Site	

ABSTRACT

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

Seismic attenuation studies were conducted in two areas (A and B) where rock excavation is anticipated at the Portsmouth, Ohio, Gaseous Diffusion Add-On site. Ground and structure motions were measured from detonation of various charge weights to seismically calibrate the site and provide explosive use limits criteria for rock excavation operations. The data were analyzed and blasting criteria established as follows: (Continued)

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20. ABSTRACT (Continued).

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(1) Charge limits which will minimize public annoyance and prevent residential or industrial structure damage at the site are: included.

				Risk of	
Area	Type of Shot	Maximum Explosive per Delay* lb	Maximum Explosive per Round lb	Residential Damage	Moderately Sensitive Structure Damage
A	Production	300	3000	1/2500	<1/25,000
A	Presplitting	--	300	1/2500	<1/25,000
B	Production	100	1500	1/2500	<1/25,000
B	Presplitting	--	100	1/2500	<1/25,000

* Delays of approximately 10 msec appear reasonable in the light of the observed period of the motion.

(2) The probability of internal component damage in the moderately sensitive structures cannot be accurately determined because the available response data are insufficient. If the risk to moderately sensitive structures stated above is unacceptable, then the Area B recommendations should be applied to both Areas A and B or one of two other procedures should be followed. One is to gain additional data during the early phases of excavation blasting for further analysis and the second is to limit the charge/delay to 100 lb. The latter two procedures will reduce the risk significantly and in the last, the maximum charge/delay (100 lb) is no larger than that already used in a test at the site.

ABSTRACT

THE CONTENTS OF THIS REPORT ARE NOT TO BE USED FOR ADVERTISING, PUBLICATION, OR PROMOTIONAL PURPOSES. CITATION OF TRADE NAMES DOES NOT CONSTITUTE AN OFFICIAL ENDORSEMENT OR APPROVAL OF THE USE OF SUCH COMMERCIAL PRODUCTS.

PREFACE

This investigation was conducted by the Earthquake Engineering and Vibrations Division (EE&VD) of the Soils and Pavements Laboratory (S&PL) of the U. S. Army Engineer Waterways Experiment Station (WES) during the period November 1976-May 1977. It was sponsored by the U. S. Energy Research and Development Administration, Oak Ridge, Tennessee.

Field tests were conducted by Mr. J. R. Curro, Jr., with the assistance of Messrs. M. B. Savage, D. H. Douglas, W. L. Reynolds, and P. H. Parks. Mr. Savage was responsible for the field electronic instrumentation and data recovery. Analysis of the data and preparation of this report were accomplished by Mr. Curro, Dr. P. F. Hadala, and Mr. G. B. Landers. The project was supervised by Mr. R. F. Ballard, Jr., Chief, Geodynamics Branch (EE&VD). General direction was provided by Mr. J. P. Sale, Chief, S&PL, and Dr. F. G. McLean, Chief, EE&VD.

COL J. L. Cannon, CE, was Director of the WES during the investigation and preparation of the report. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	0.02540	metres
pounds (mass)	0.4535	kilograms
feet	0.3048	metres
feet per second	0.3048	metres per second
inches per second^2	0.02540	metre/second^2 (m/s^2)

SEISMIC ATTENUATION TESTS AT THE PORTSMOUTH, OHIO, GASEOUS DIFFUSION ADD-ON SITE

PART I: INTRODUCTION

Background

1. In the planned expansion of the Portsmouth, Ohio, Gaseous Diffusion Plant, earthwork including extensive shale bedrock excavation may be necessary. Should the shale be too difficult to rip, blasting will be necessary to excavate it. Industrial processes involving radioactive materials will be in operation in some buildings at the plant during the construction period. The term "moderately sensitive" structures has been adopted by the U. S. Energy Research and Development Administration (ERDA) to identify these buildings. It is necessary to have a very high degree of confidence that vibrations will not cause any safety problems in these structures before blasting can be permitted. To achieve this level of confidence, it is necessary to conduct a carefully controlled blasting test program at the site and measure (a) the motion of the ground as a function of distance from the explosion and (b) the response of the moderately sensitive structures. An investigation of this type was conducted with the K-25 Plant at Oak Ridge, Tennessee,[1] and that investigation was used as a model for this study.

2. Other buildings in the Portsmouth plant are considered as "minimum sensitivity" structures because they do not house radioactive processes or materials. Also in the vicinity of the proposed rock excavation areas are private residential and farm buildings. Protection of these structures from damage and the minimization of annoyance to their occupants are also important. Because the consequences of failure are not nearly as serious, however, the degree of confidence in success need not be as high as it must be in the case of the "moderately sensitive" structures.

Purpose and Scope

3. The purpose of this investigation was to determine the attenuation of explosion-induced ground motion amplitudes with range (R) from buried explosions in order to seismically calibrate the site and provide the data base needed to write explosive use limits criteria that will (a) keep blasting vibrations at the "moderately sensitive" structures within safe levels, (b) protect conventional structures, and (c) minimize public annoyance.

4. The field investigation consisted of a high explosive test ground motion measurement program consisting of nine shots ranging in explosive weight from 5 to 100 lb* with 32 motion-time histories measured from each shot. The data obtained were then analyzed to (a) develop ground motion attenuation curves, (b) determine relative amplitudes of structure to ground motion, and (c) develop guidelines that will assure that blasting vibrations will be less than levels known to be acceptable.

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* A table of factors for converting U. S. customary units to metric (SI) units is given on page 4.

PART II: TEST PROGRAM

Location

5. Ground motion measurements were made in a series of explosive tests conducted within the boundaries of the Portsmouth Gaseous Diffusion Plant known as the Add-on-Site during the period 1-22 November 1976. The test site is shown in Figure 1. Explosive tests were conducted in two of the areas where rock excavation is anticipated. These are labeled Areas A and B in the figure. Also shown in the figure are the nearest moderately sensitive structures (Buildings X-300, X-326, X-333, X-710, and X-633-2B), the nearest minimum sensitivity structures, and the nearest residential/farm buildings which are located just to the east of the boundary fence. Special note should be taken of the locations of Building X-100 and the Security Office as observers were stationed in these facilities during the tests.

Tests Conducted

6. Nine explosive tests were conducted as indicated in Table 1. The explosive charges ranged in weight (W) from 5 to 100 lb of Vibronite-S. All the charges were detonated more than 25 ft below the ground surface and were below the top of rock. All but test 7 were located below the level of groundwater in the drill hole. In each shot, vertical, radial, and transverse free-field ground surface particle velocities were measured at six different ranges (R) from the detonation point. Structural response particle velocities (six each vertical, radial, and transverse) were measured inside selected buildings for each shot. Table 1 designates the number of the borehole(s) containing the explosive. Each hole was stemmed after loading. Only one test, No. 7, involved the use of a delay; all others were one-point detonations. The shot number indicates the order in which the tests were conducted. The weight of explosives used was increased gradually in shots 1-6. After each shot the test data were examined before proceeding to the next test

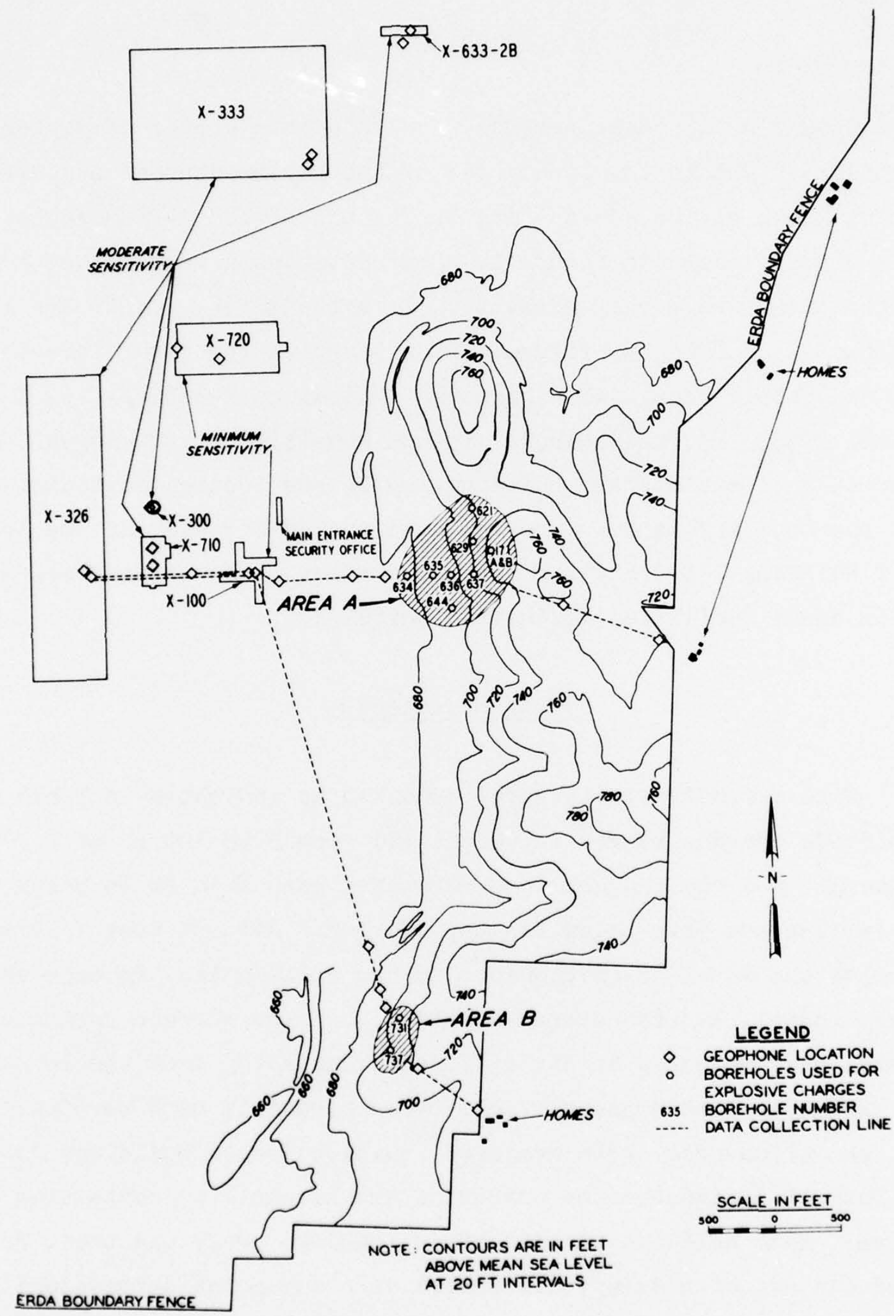

Figure 1. Location plan

to insure that peak particle velocities at moderately sensitive structures were always less than those safely experienced by similar structures at the Oak Ridge Plant (see Reference 1). The reactions of observers in various buildings to the various shots are noted in Table 1. Whether the observers actually were aware of motion or responded to noise associated with venting of the borehole is questionable. At any rate, they were aware that the explosion had occurred in tests 4-7 but were not sufficiently affected to register annoyance or complaint.

Instrumentation

7. Data for the studies were acquired by both battery and alternating current (AC)-line powered instrumentation. Three separate instrument systems were employed to retreive test data. The first system, consisting of AC-line powered equipment, monitored 24 data channels from Buildings X-100, X-326, and 4 free-field locations. This system contained two oscillographs (12-in.-wide paper), direct current (DC) amplifiers, and other equipment necessary for sine wave calibration. Oscillograph galvanometers covered the frequency range from DC to 1000 Hz, and the DC amplifiers operated from DC to 10 kHz. A root mean square (rms) voltmeter measured the calibration voltage, and the equivalent velocity value was calculated from the manufacturer's reported sensitivity for each transducer.

8. The second system, housed in a small van, was battery-powered and recorded six channels of data from Buildings X-633-2B, X-333, X-720, X-300, and X-710. This system consisted of one oscillograph (3-5/8-in.-wide paper), WES-made DC amplifiers, and sine wave calibration equipment. Oscillograph galvanometers covered the frequency range from DC to 200 Hz, and the amplifiers operated from DC to 1250 Hz. Calibration methods were the same as these described above.

9. The third instrumentation system consisted of a self-contained battery-powered, portable unit that monitored data from six channels in the east boundary area. The data were recorded on 3-5/8-in.-wide oscillograph paper using WES-made DC amplifiers and DC calibration steps.

Oscillograph galvanometers covered the frequency range from DC to 60 Hz, and the DC amplifiers operated from DC to 5 kHz.

10. Velocity-type geophones (to detect the seismic signals) were used in conjunction with the above-mentioned instrumentation. Three different geophone models had to be employed during the investigation because of installation and sensitivity requirements. Three geophones (forming a triaxial array with one vertically and two horizontally oriented) of each model were housed as a unit in a waterproof container. At the most distant ranges, all of the geophones in a unit had a sensitivity of 6 volts per in./sec with a natural frequency of 1.0 Hz. For intermediate ranges geophones with a sensitivity of 1.75 volts per in./sec and a natural frequency of 4.5 Hz were used. For the measurements closest to the explosive detonations, units with a sensitivity of 96.3 volts per in./sec and a natural frequency of 2.5 Hz were used. All geophones were damped approximately 70 percent to insure flat frequency responses.

Subsurface Conditions

11. Numerous borings have been drilled at this site. Only those used for shot holes are shown in Figure 1. Soil profiles have been interpreted from the logs of these borings; they are reported in Reference 2. Seismic survey data were also obtained at the site and they are reported in Reference 3.

12. From these sources, it is known that the soil profiles to the east and to the west of the potential blasting areas are different. To the east, the topography is fairly level and so is the surface of the shale bedrock. The bedrock is covered by 3.5 to 11 ft of soil and the groundwater table does not exist in the rock. To the west, the ground surface drops abruptly to the plain on which the present plant is situated. At the edge of the abrupt drop is a soil-filled, buried valley about 35 to 65 ft deep and 500 to 1200 ft wide. Under the plant area, the shale bedrock is at a depth of 30 to 35 ft and the depth to ground water is 10 to 20 ft. At this site the average seismic P-wave velocity of the near surface shale bedrock ranges from 8025 to 9575 ft/sec.

PART III: FREE-FIELD RESULTS AND ANALYSIS

Wave Forms

13. Figures 2 and 3, respectively, show vertical and radial ground surface particle velocity time histories at four ranges from a 100-lb buried burst in Area A (i.e. shot 6). The gages were located to the west of Area A and were 315 to 1950 ft from the shot point. The duration of motion exceeded 1 sec in all cases; at the closest range, the amplitude decayed into the noise level of the instrumentation system and had not really stopped at the end of the time period shown in the figures. At each location, the motion can be described as an initial train of body (P and S) wave motion followed by a lower frequency train of surface waves whose peak velocity amplitudes equal or exceed those of the body wave trains.

Particle Velocity

14. Figure 4 is a log-log plot of maximum single peak surface particle velocity (v) versus $R/W^{1/3}$. In this plot W is the weight of explosive per delay. In all but test 7 it also is the total explosive weight. Figure 4 contains all the free-field data obtained. This form of plot is a conventional way of presenting the attenuation of ground motion from buried spherical charges and is derived from consideration of dimensional analysis. To provide a frame of reference, the range of data obtained in the seismic attenuation test program at the K-25 plant at Oak Ridge[1] is also shown in the figure. As indicated in the figure, higher amplitudes of motion occurred at a given range at the locations shown in Figure 1. The "working curve" in Figure 4 is a near upper bound to all the data obtained. Only two of 162 data points lie above it. While the working curve shown in the figure has a slope of -2, the data are best fit by a curve which has a slope of ≈-1.7. Another point to be noted is that the data in Figure 4 are for fully contained bursts, and are thus most appropriate for the ground motion

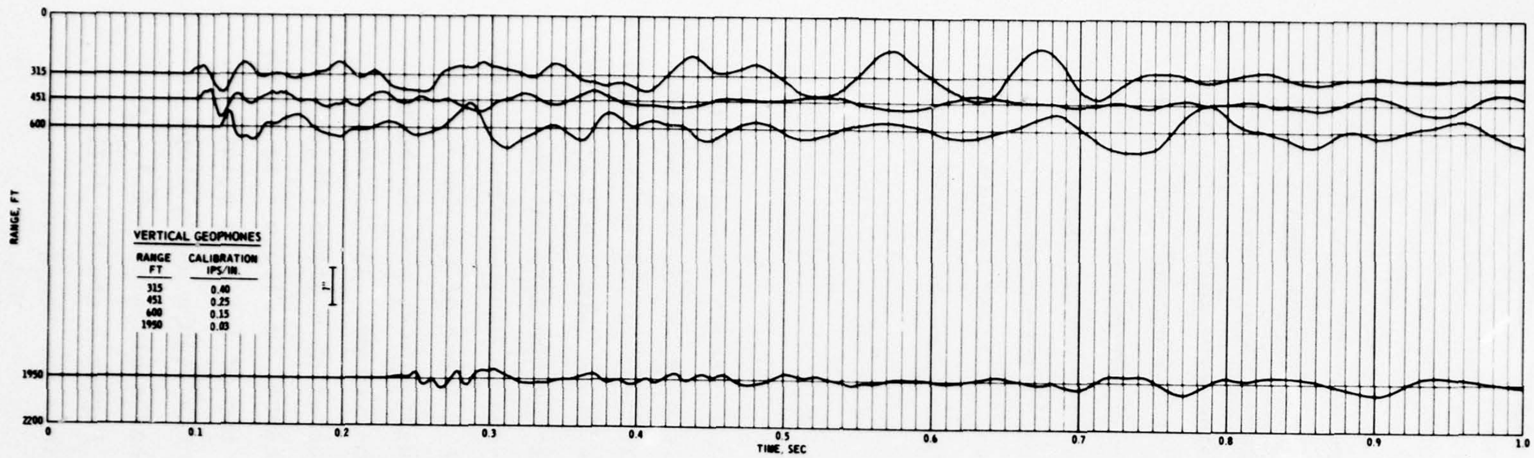

Figure 2. Vertical particle velocity versus time for four locations west of Area A in shot No. 6

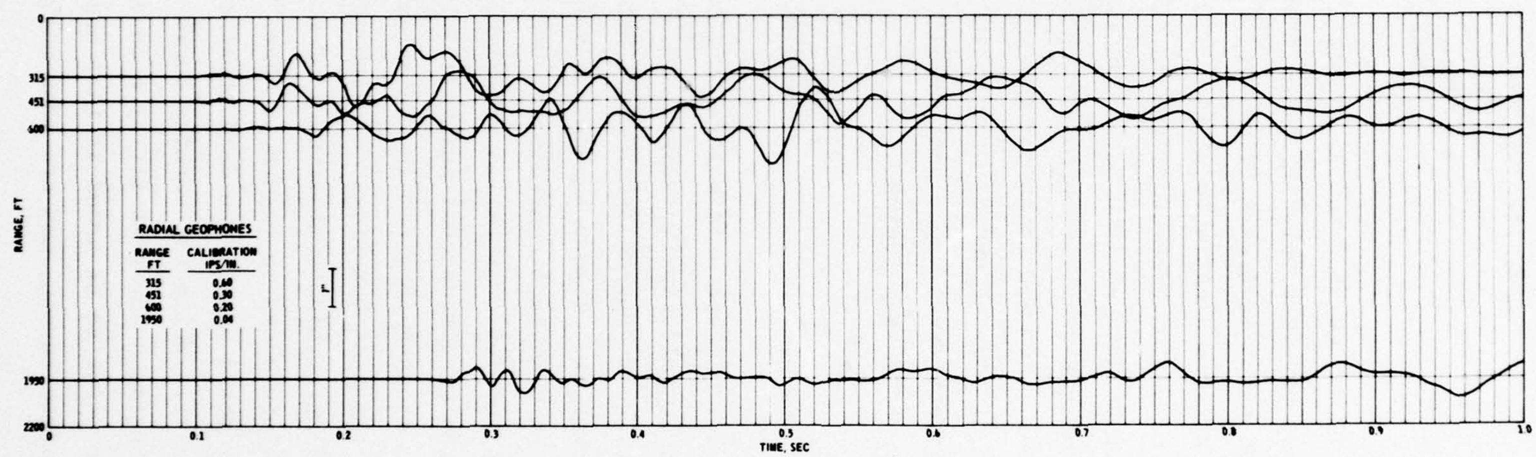

Figure 3. Radial particle velocity versus time for four locations west of Area A in shot No. 6

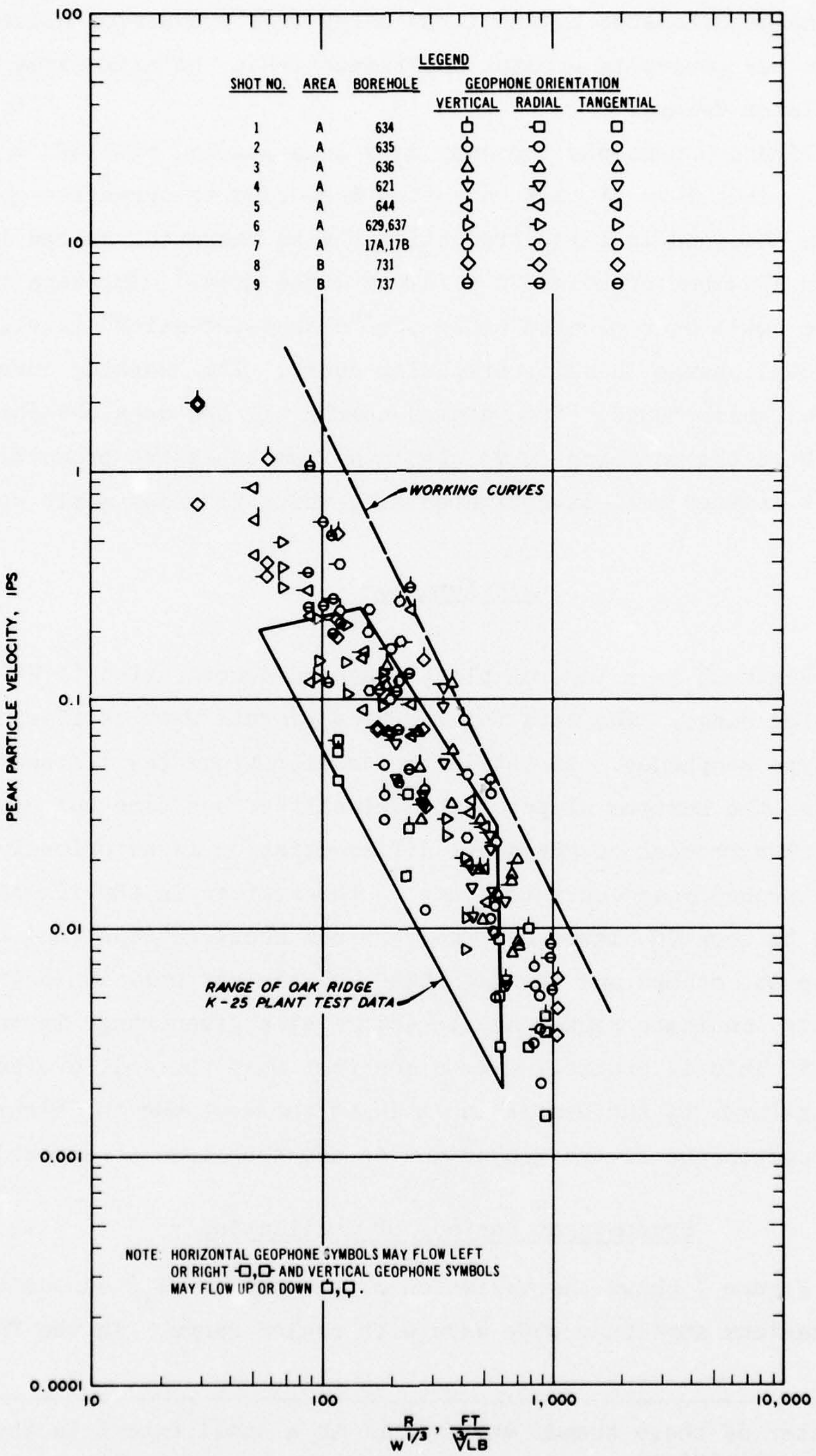

Figure 4. Maximum free-field particle velocity versus scaled range

from the charge detonated by the first delay of a production blast since that charge has generally greater confinement than the explosives detonated by later delays.

15. Figure 5 presents the same data in a log-log plot of v versus $R/W^{1/2}$. This form of plot has often been used to summarize ground motion data obtained in large production blasts where the charge is distributed in a number of holes in a fairly large area.[4] The data from shot 7 have again been plotted using the "charge-per-delay" (i.e., one-half the total charge in this particular case). The "working curve" in this figure, which bounds (from above) nearly all the data obtained, is slightly above the bounding curve obtained from extensive production blasting at another well-investigated site which also had shale bedrock.[5]

Acceleration

16. Figure 6 is a log-log plot of scaled acceleration ($a \cdot W^{1/3}$) versus scaled range. The data for the test program were obtained with velocity-type geophones. To obtain the accelerations (a) plotted in this figure, the maximum slope of the velocity versus time curve was measured. The process of graphical differentiation is notoriously inaccurate and probably accounts for some of the scatter in the figure. Two trends can be seen in Figure 6. The vertical accelerations tend to be higher than the others and the data taken on the easterly lines (the solid points) indicate higher accelerations at a given range in that direction.* This is probably due to the fact that the soil overburden is much shallower to the east than it is to the west and the higher frequency components of the ground motion are thus less attenuated.

Predominant Periods of Oscillation

17. Figure 7 shows the variation of the period (T_1) associated with the maximum amplitude body wave with scaled range. In the form of

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* The latter of these trends was evident to a small extent in the peak particle velocities.

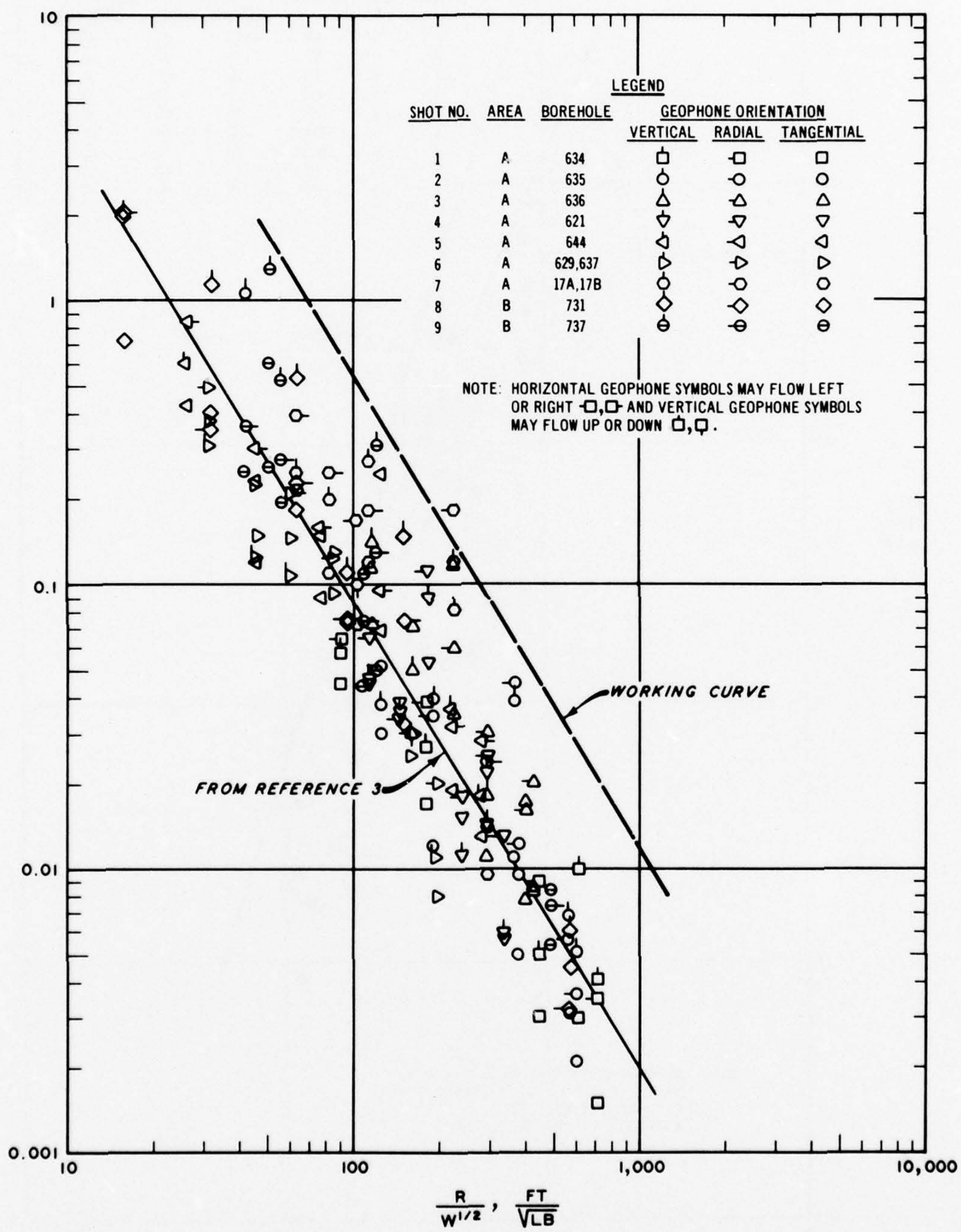

Figure 5. An alternate presentation of the maximum particle velocity data

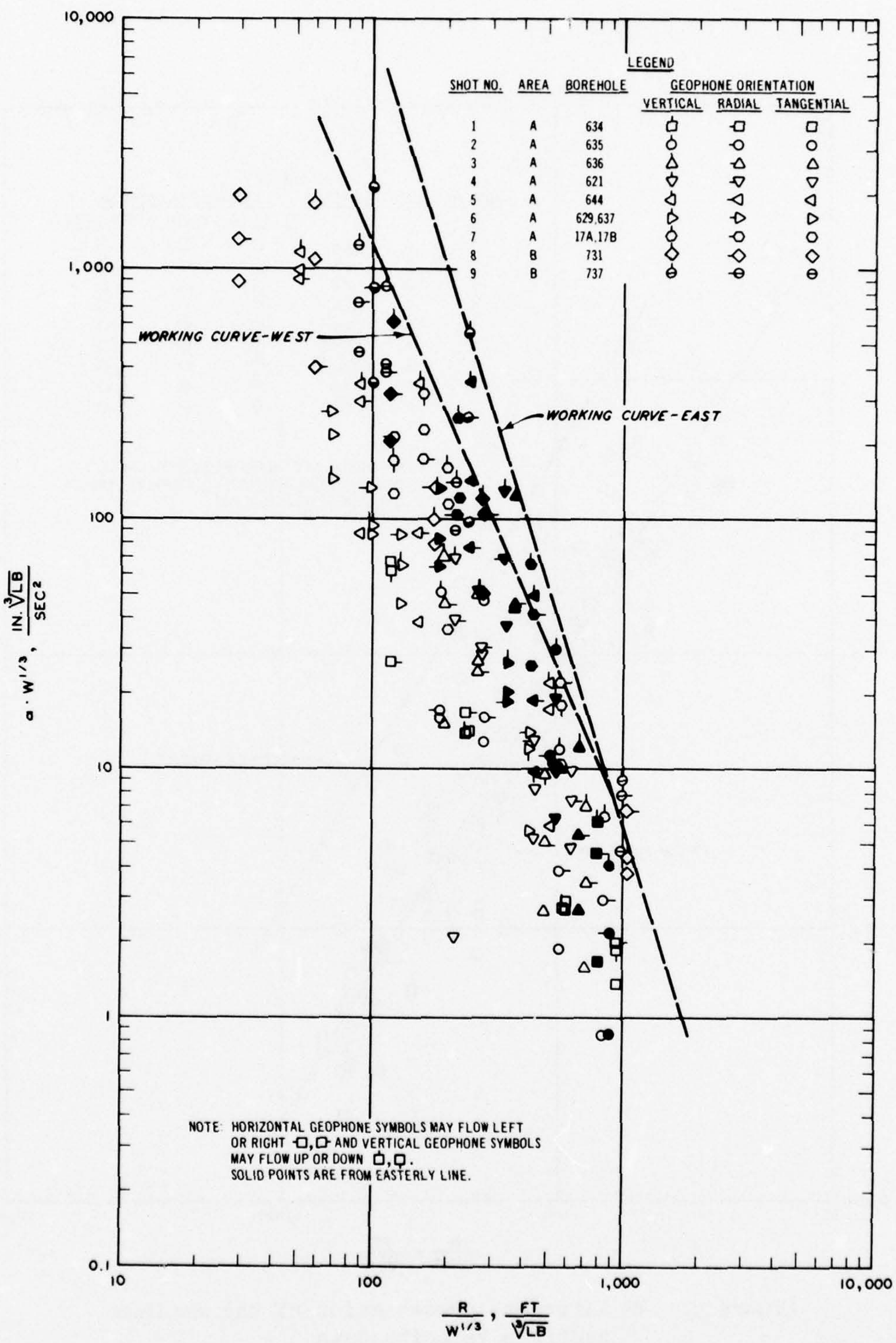

Figure 6. Scaled acceleration versus scaled range

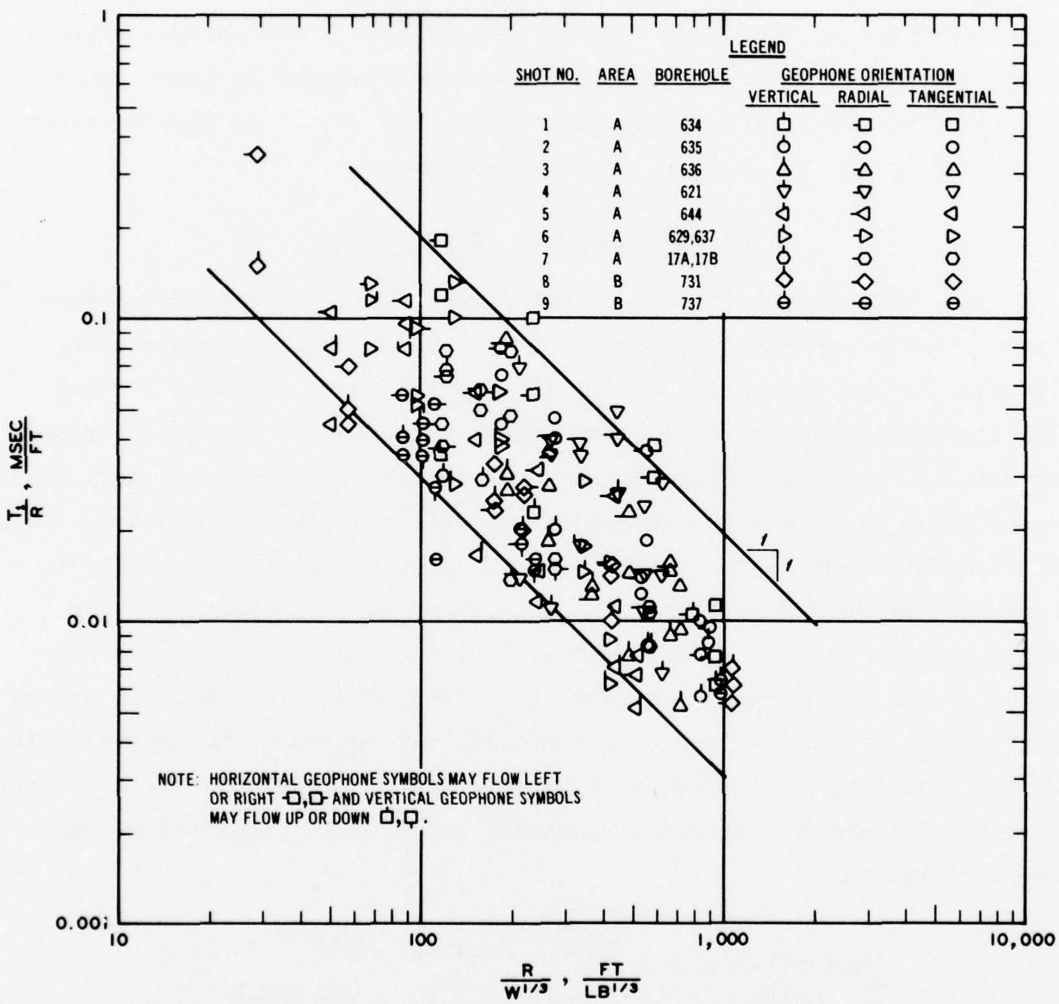

Figure 7. Scaled period of body wave velocity peak versus scaled range

plot used (log T/R vs log $R/W^{1/3}$) a -1 slope indicates periods that are independent of range and proportional to $W^{1/3}$, while a -1/2 slope indicates periods that are proportional to the square root of R and the 1/6 power of W . The periods appear to be weakly dependent on W and essentially independent of R . They ranged from 7 to 100 msec and averaged 22 msec. Figure 8 shows the period T_2 associated with the late arriving low frequency velocity pulses (i.e., the surface waves). These periods ranged from 28 to 148 msec and averaged 84 msec. Most of the velocity peaks were associated with period T_2 . As charge weight increases, both T_1 and T_2 should increase.

Safety Analysis: Amplitudes

18. Reference 4 indicates that a peak particle velocity of more than 2 in./sec can cause damage to frame and residential structures (particularly older residences). In this reference (Figures 7-2 and 7-3), there are 136 case histories where there was no damage to framed structures at velocities in excess of 2 in./sec and there are only four cases where light damage occurred at velocities between 1 and 2 in./sec. Based on these data, the probability of light damage to framed structures at particle velocities of 2 in./sec or less is about 4/140 or about one chance in 40. Reference 4 indicates that there are no cases where damage has occurred at velocities less than 1 in./sec. As stated previously, working curves that approximately represent the upper limit of the data have been drawn in Figures 4 and 5. Tabulated below are the distances at which a 2-in./sec particle velocity is predicted by the working curves:

Explosive/Delay lb	$R/W^{1/2}$ Scaling ($45\ ft/lb^{1/2}$)	$R/W^{1/3}$ Scaling ($90\ ft/lb^{1/3}$)
50	320 ft	330 ft
100	450 ft	420 ft
200	640 ft	530 ft
500	1000 ft	710 ft
1000	1420 ft	900 ft

The probability of exceeding 2-in./sec particle velocity for these

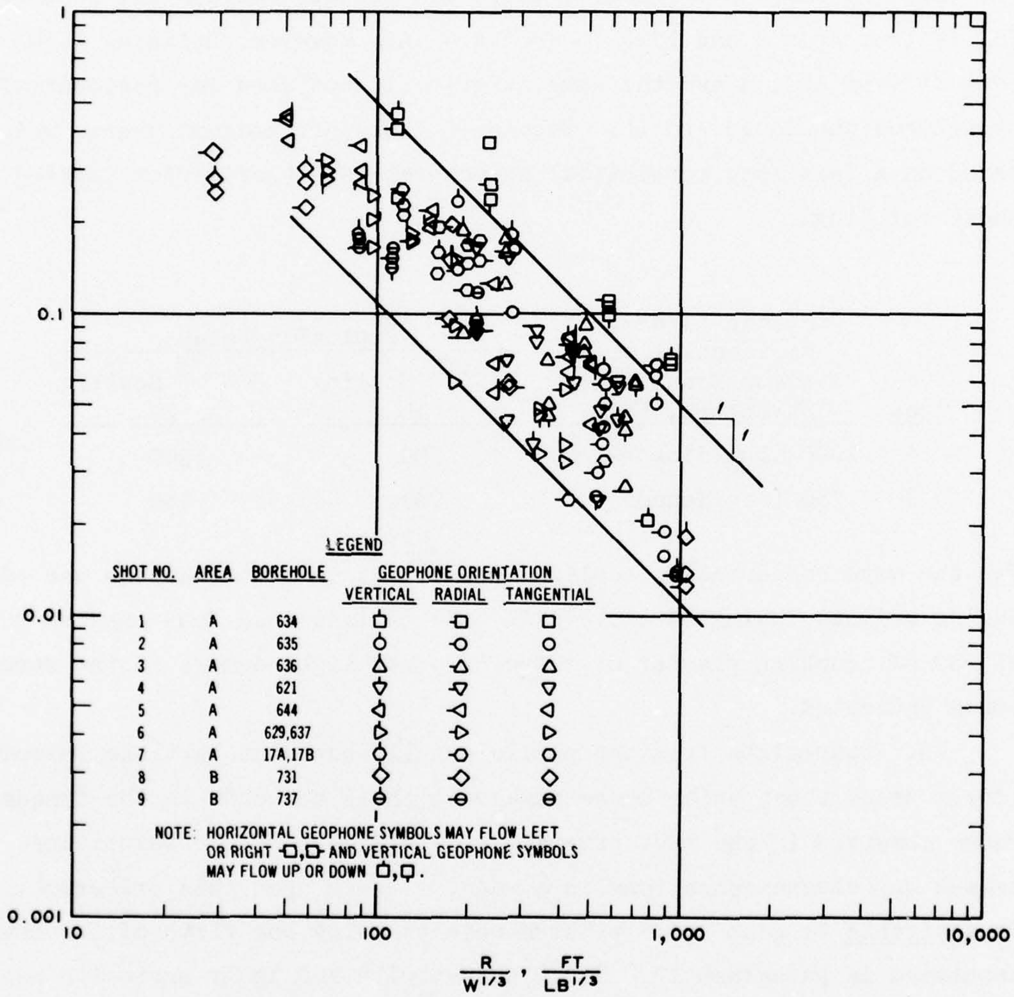

Figure 8. Scaled period of surface wave versus scaled range

charges and distances (using the more conservative $R/W^{1/2}$ scaling) is about one chance in 90. Thus for these charges and distances the combined probability of exceeding this velocity and causing light damage to framed structures due to the blasting vibrations is less than three chances in 10,000.

19. As shown in Figure 1, there are private residential structures 750 ft from Area B and 1500 ft from Area A. However, Building X-100 is 1000 ft from Area A and the same safety criteria used for residential structures should govern it. Tabulated below are maximum charge weights based on a 2-in./sec residential structural safety criterion applied to these buildings:

Area	Distance to Nearest Residential or Minimum Sensitivity Structure, ft	Explosive/Delay $R/W^{1/2}$ Scaling lb	Explosive/Delay $R/W^{1/3}$ Scaling lb
A	1000 (Building X-100)	500	1300
B	750 (residences)	280	580

For the more conservative scaling ($R/W^{1/2}$) it is felt that the use of charge weights indicated above will produce less than four chances in 10,000 of cracking plaster or inducing other light damage in the structures indicated.

20. Complaints from the public usually occur at particle velocity levels below those which cause damage to their homes.* In the frequency range observed in the test program, 0.5-in./sec particle velocities caused unpleasant sensations in humans.[4] Based upon this criterion, it is desirable to keep the explosive weights below one fifth of the levels tabulated in paragraph 19. Since a test with 100 lb of explosive has already been conducted at this site without causing any adverse reaction from the public or from the work-force, and since it produced a maximum

* As indicated in Table 1, a 100-lb shot in Area A was noticeable but was not considered troublesome or irritating by personnel in Building X-100. The maximum particle velocity measured there was less than 0.03 in./sec.

particle velocity of only 6 percent of the level deemed troublesome to people at Building X-100, the levels tabulated below should not cause particle velocities which result in complaints.

Area	Distance to Nearest Residential or Minimum Sensitivity Structure, ft	Explosive/Delay $R/W^{1/2}$ Scaling lb	Explosive/Delay $R/W^{1/3}$ Scaling lb
A	1000	300	750
B	750	170*	350

* See paragraph 22, other criteria will be shown to control.

21. From the working curves shown in Figure 6, it can be determined that, if the charges calculated in paragraph 20 were used, the maximum accelerations experienced would be as follows:

Location	Minimum Range R ft	Charge/Delay from paragraph 20 lb	Acceleration from Figure 6 g
Residential structures* east of Area B	750	170	1.64*
Building X-100 west of Area A	1000	300	0.19
Building X-300 west of Area A (sensitive structure)	1900	300	0.04

* In test 9, a gage located on the eastern fence line 940 ft from a 61-lb explosion read 0.36 g, with a 15-msec period.

22. The acceleration levels for the structures to the west of the blasting areas are acceptable. To the east, however, acceleration levels are quite large. There are on record (Figure 7-2, Reference 4) only three cases of minor damage in old nonengineered structures at an acceleration level of 0.7 g in the period range measured here. All the other available data (over 100 cases) indicate no damage at acceleration levels below 1 g. Steady state acceleration of 1/2 g in the 50-100 Hz range is intolerable to humans, but short pulses of twice that

magnitude, although noticeable, are quite tolerable.[4] Hence, it is recommended that blasting at Area B be limited to that producing no more than 1.0-g short-duration acceleration at the nearby residences. This corresponds to a charge/delay of slightly less than 100 lb.

23. At the K-25 plant at Oak Ridge, safety criteria for "sensitive structures and their contents" of 0.50 in./sec and 0.15 g were adopted. (See paragraph 5, Reference 1). These criteria were found to be satisfactory in operational blasting. At the site shown in Figure 1, the sensitive structures are located at distances of 1900 ft or more from Area A and 3400 ft or more from Area B. In test 6 (a 100-lb detonation in Area A), a measurement station inside Building X-326 experienced a maximum acceleration of 0.02 g and a maximum particle velocity of 0.015 in./sec. This motion was not noticeable to occupants of the building and is far below the sensitive structure criteria used at the K-25 plant.

24. If the 0.5-in./sec particle velocity criterion is applied to the data in Figure 5, then charges of 330 lb/delay could be detonated in Area A. This is considerably less restrictive than the charge/delay limit imposed by the safety of conventional structures located closer to the blasting area (paragraph 19) and is slightly less restrictive than the charge weights that would be prudent if good public relations are desired (paragraph 20). Based on the available data, there is about one chance in 300 of exceeding 0.5 in./sec at the nearest moderately sensitive structures (Buildings X-710 and X-300) if 500 lb is the maximum charge permitted in Area A (see paragraph 19) and about one chance in 500 of exceeding this value if 300 lb is the maximum charge permitted. If the data to establish the probability of damage to a critical (from the point of view of safety) component within the moderately sensitive structures at a 0.5-in./sec particle velocity were available, the combined probability of damage to a sensitive structure could be determined. Unfortunately, such data do not exist. From the experience at the K-25 plant and industrial vibration data summarized in Reference 1, it can be estimated that the probability of damage at this velocity is smaller than one chance in 50 but how much smaller is unknown. Thus, the probability of damage could be as high as one in 15,000 for the 500-lb

charge and one in 25,000 for the 300-lb charge.

25. Conditions at this site are radically different from those investigated in Reference 1. In that case, it was desired to blast in close proximity (≈200 ft) to a sensitive structure. In this case, no structures of any kind are in close proximity. However, residential buildings are much closer than the sensitive structures, and blasting charge limits designed to avoid public annoyance (300 lb in Area A and 170 lb in Area B) are very conservative with respect to safety of conventional structures. Such charges would have a very low probability of causing damage at the moderately sensitive structures (i.e., 1/15,000 to 1/25,000). However, it is not completely clear that these probabilities of damage are sufficiently small. The authors are not fully cognizant of the consequences of blast-induced vibration damage to a moderately sensitive structure containing radioactive processes.

26. Should ERDA feel that the estimated risk is too large, two courses of action are available. One is to gain additional data during the early phases of construction blasting. Presently one has a very high degree of confidence, based on actual tests, that a charge of 100 lb/delay will not cause damage in moderately sensitive structures. Initial production blasting in Area A should be limited to this level and increased in not more than 50-lb increments while the motion responses of the ground floors in Buildings X-300, X-710, and X-326 are monitored. Further increases should be suspended when (a) the charge/delay reaches 300 lb, (b) the motion in any of these structures reaches or exceeds 0.5 in./sec or 0.15 g's, or (c) any indications of rough operation of industrial equipment or processes occur in these buildings. The second course of action is to limit the charge/delay to 100 lb. Since data (see Table 2) indicate motions due to 100-lb explosions are typically about 2-1/2 times the background vibration levels in most of the sensitive structures, the probability of damage from 100-lb charges is infinitesimal.

27. Additional factors should be mentioned that bear subjectively on the issue of risk. The first concerns containment of the explosions. The tests conducted were fully contained explosions. They are similar

in confinement to that portion of the round detonated by the first delay in a production blast or in presplitting operations. Later delays produce less motion because of relief at the free surface generated by the charge detonated in an earlier delay. This tends to make the explosive weight limits recommended conservative.

28. The second factor concerns the use of delays. Millisecond delays reduce the body-wave amplitudes by destructive interference.* The body-wave periods (paragraph 17) averaged 22 msec, and nominal 10- to 15-msec delays can effectively minimize the body wave amplitudes.

29. On the other hand, the distances between the blasting areas and the buildings of interest are such that most of the peak particle velocities measured were associated with larger period surface waves (this period averaged 84 msec). To produce constructive interference in these waves requires a much larger delay. As shown in Figures 2 and 3, at the 315- to 600-ft range, a delay of approximately 40 to 50 msec in any superimposed wave would be ideal. However, since several cycles of motion whose amplitudes are near the peak occur one after the other, a somewhat larger delay would produce reinforcement. Since surface wave periods increase with range and charge weight, the delay that optimizes interference for one range will actually result in reinforcement at another range in the same shot or at the same range in other shots of different yield. Only by using a very long delay (i.e., approximately 750 msec or about 10 times the predominant period) can nonreinforcement of surface waves be assured if one follows this line of reasoning.

30. Figure 9 shows the ground motion data from shots 5, 6, 7, and 9. Shot 6 was a one-point detonation of 100 lb of Vibronite-S while shot 7 consisted of two 50-lb detonations separated by 110 msec. Both shots were fired in Area A. Tests 5 and 9 were nominal 60-lb nondelay detonations in Areas A and B, respectively. Plotted in the figure is the largest velocity component (either vertical, radial, or, occasionally, transverse) that occurred at a given range in a given shot. In

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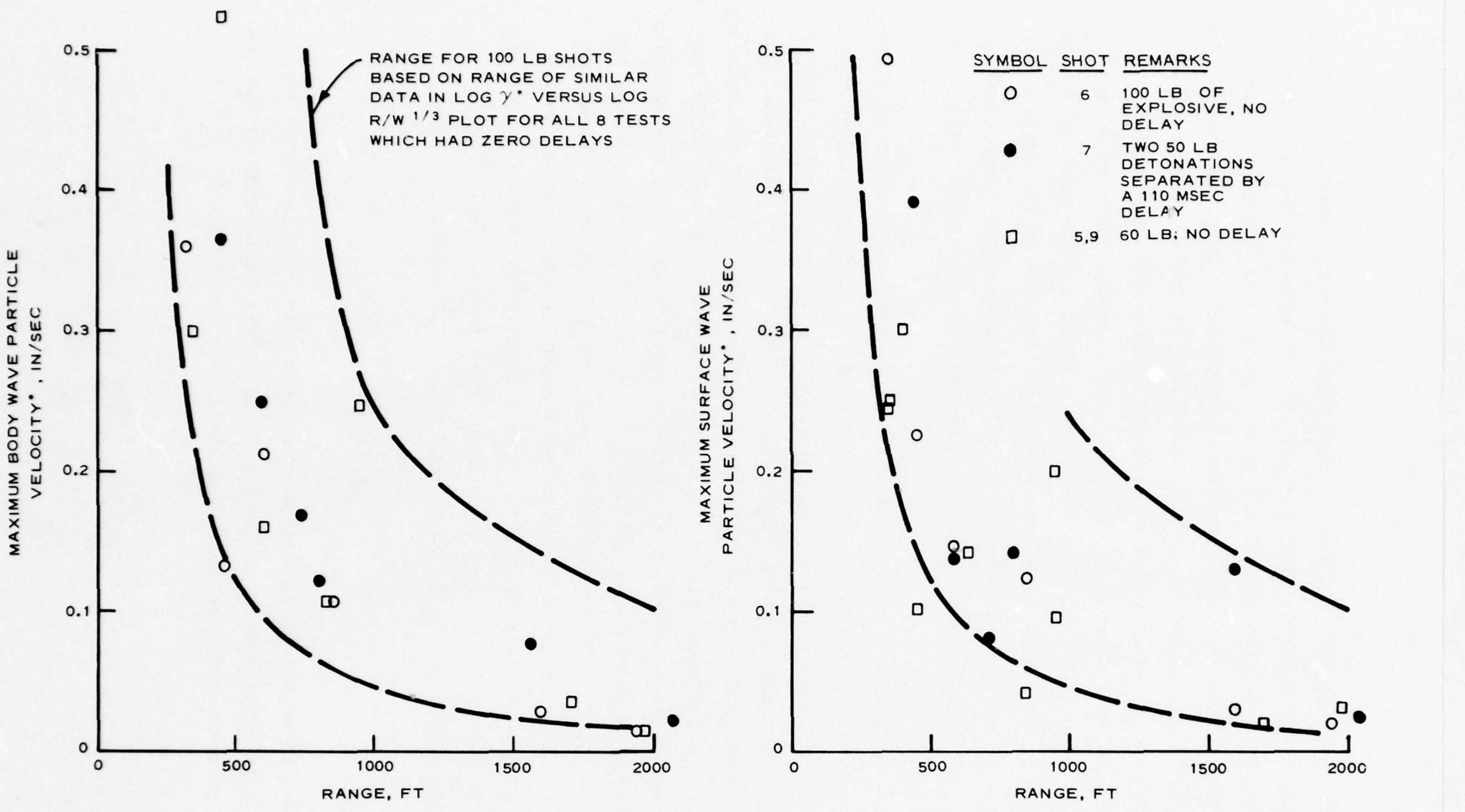
* In steady state harmonic motion, destructive interference is maximized when the delay of the second pulse is exactly one half the period of the two pulses.



* IRRESPECTIVE OF ORIENTATION (VERT, RADIAL OR TRANS.)

Figure 9. Effect of a 110-msec delay on particle velocity amplitudes

the left plot are the peaks associated with the body wave train; on the right are the comparable data for the surface wave train. The data in Figure 9 indicate that the effect of the particular delay used was to actually increase the particle velocity amplitudes over the values seen in the nondelay detonation of the same total explosive weight. Two 50-lb shots delayed by 110 msec produced roughly the same motions as the 60-lb nondelay shots. However, if one uses the range of data in Figure 4 to predict the range of velocity for a 100-lb nondelay detonation, the dashed lines in Figure 9 result. In view of the large range of data scatter, the differences in velocity at a given range between shots 6 and 7 or between 5, 9, and 7 are not considered statistically significant.

31. Reference 5 contains a sufficient amount of production blasting vibration data to obtain a statistically significant picture of the use of 5- and 9-msec delays. In this reference, ground motions 600 to 4000 ft from nondelay and 5- and 9-msec delay shots are compared. The site in that study was also in a shale bedrock, and most of the velocity peaks were associated with surface waves whose periods were 80 to 120 msec. For a given amount of explosive/delay (250-350 lb), the velocity peaks for 9-msec delays were less than they were for 5-msec delays and these were in turn less than for nondelay shots. Based on these data, it can be seen that msec range delays should be effective and should keep the peak particle velocities from a round involving delays and a charge per delay of W no larger than those from a single fully-contained charge of W fired without the use of delays.

Summary

32. Blasting can be conducted at this site with less than one chance in 2500 of causing minor damage at nearby residences or nonsensitive structures if the following limits are observed:

Area	Type of Shot	Maximum Explosive per Delay W, lb	Delay Interval msec	Maximum Explosive per Round lb
A	Production with delays	300	≈10	3000
A	Presplitting or production without delays	--	--	300
B	Production with delays	100	≈10	1500
B	Presplitting or production without delays	--	--	100

The total weights of explosives for the production shots are purely arbitrary limits but are within the range of the test data in Reference 5 (a case history with many similarities to the problem at hand). The maximum charge per delay levels listed above have been set with minimization of annoyance of the public as well as prevention of residential damage in mind.

33. These same charges have a probability of causing damage in the moderately sensitive structures of <u>less</u> than one in 25,000. How much less the probability is cannot be determined without a detailed understanding of what elements within the structure are most sensitive and the location of a significant body of data on the response of such elements to vibratory motions. This, the writers were unable to do. Paragraph 26 recommends alternate courses of action that can be followed if a risk of less than one in 25,000 is considered too high.

PART IV: MOTION IN EXISTING STRUCTURES

Measurements

34. Measurements were made on the first and second floors of Buildings X-100 and X-326 for all nine shots. In addition, Buildings X-300, X-333, X-633-2B, X-710, and X-720 were monitored on a rotating basis for each shot. Table 2 summarizes the peak structure motions recorded in the four largest shots (5, 6, 7, and 9) and the background vibration levels in these structures. The motions seen during the experimental detonations were always less than seven times the background level of vibration in the sensitive structures and were typically less than two and one-half times the background level.

Amplification

35. The recorded in-structure motions were compared with the predicted values using the near-upper bound working curves in Figures 4 and 6. The ratio of in-structure motion to free-field ground motion tended to increase with scaled range ($R/W^{1/3}$) and to be higher at second-floor measuring stations than at ground-floor stations. Figure 10 shows the ratio of in-structure to free-field maximum particle velocity for the four largest shots in the test program. The trends discussed above are evident in the figure. Also shown in the figure are the scaled ranges corresponding to the maximum charge limit recommendations and minimum distances to selected structures. By extrapolation, it can be seen that the amplification ratio (as defined here) does not exceed 1.2 at the recommended limit. This means that the working-curve free-field motions nearly upper bound the structure motions actually recorded.

36. Figure 10 does not mean that the structural motions will not be larger than the ground motions. In fact, they usually will be, especially in the upper stories of the structure. However, from the figure, it is clear that only rarely in a construction blasting operation at this site will the structure motion amplitude exceed the working curve values for the free field and then by only 20 percent.

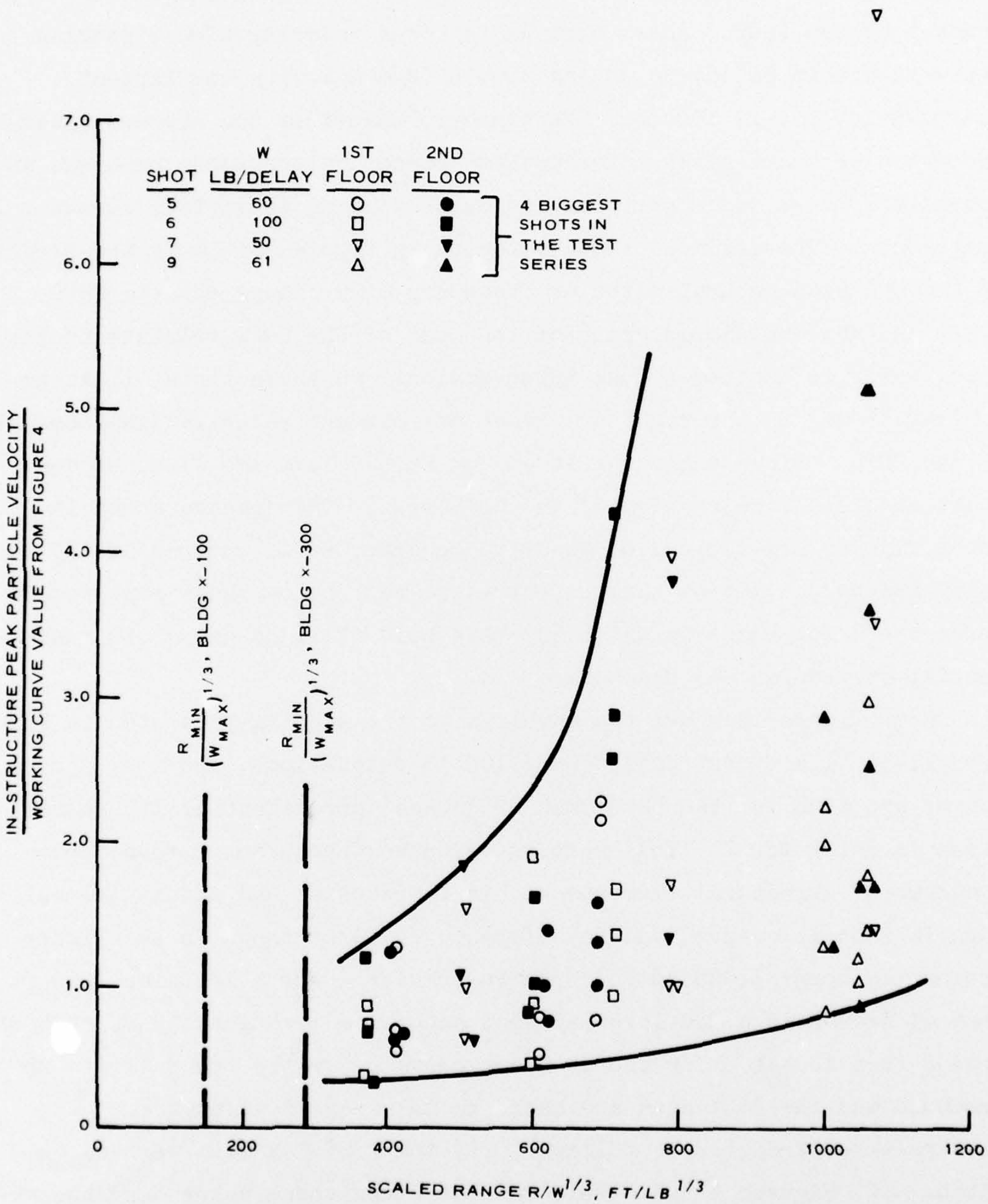


Figure 10. Velocity amplification versus scaled range for shots 5, 6, 7, and 9

Shock Spectra

37. Figures 11-14 present 0 and 5 percent damped single-degree-of-freedom system (SDFS) shock spectra for four velocity-time histories measured within buildings during shot 6 (the one with the largest charge/delay, i.e., 100 lb). Reference 6 describes the use and interpretation of shock spectra for dynamic structural response problems and provides some guidance as to the degee of damping in various structural components. The maximum pseudo velocity in Figures 11-14 is the product of the undamped natural circular frequency of a linear elastic SDFS times the maximum displacement of the mass of the SDFS relative to its base, which is excited by the input motion. On these plots, lines ascending 45 deg to the right are lines of constant relative displacement of the SDFS. Lines ascending at 45 deg to the left are lines of constant absolute acceleration of the SDFS mass. The spectra shown in these figures are typical of those to be expected if charges of 100 lb/delay are used. All of these spectra are well below those reported in Reference 7 for cases in which the threshold of light damage to residential structures was reached.

38. Figure 15 shows the envelope to the spectra presented in Figures 11-14 (i.e., test data from a 100-lb detonation), and the 3 percent damped spectrum for the threshold of damage to residential structures given in Reference 7. This damping value was shown to be reasonable for a number of structural elements within residential and industrial buildings in that reference, and in Reference 8. Also shown in the figure are nearly upper bound damped spectra predicted for a location 1000 ft west of Area A in a 300-lb/delay shot and for a location 750 ft east of Area B in a 100-lb/delay shot. These charges are the upper limits recommended and the distances are those to the nearest structures. The spectra were predicted as follows: (1) the $R/W^{1/3}$ values were calculated. (2) Figures 4 and 6 were entered using these values and the velocity and acceleration on the working curves were determined. (3) Spectral amplification values obtained from Reference 7 (4.0 for velocity and 2.5 for acceleration) were applied to obtain the

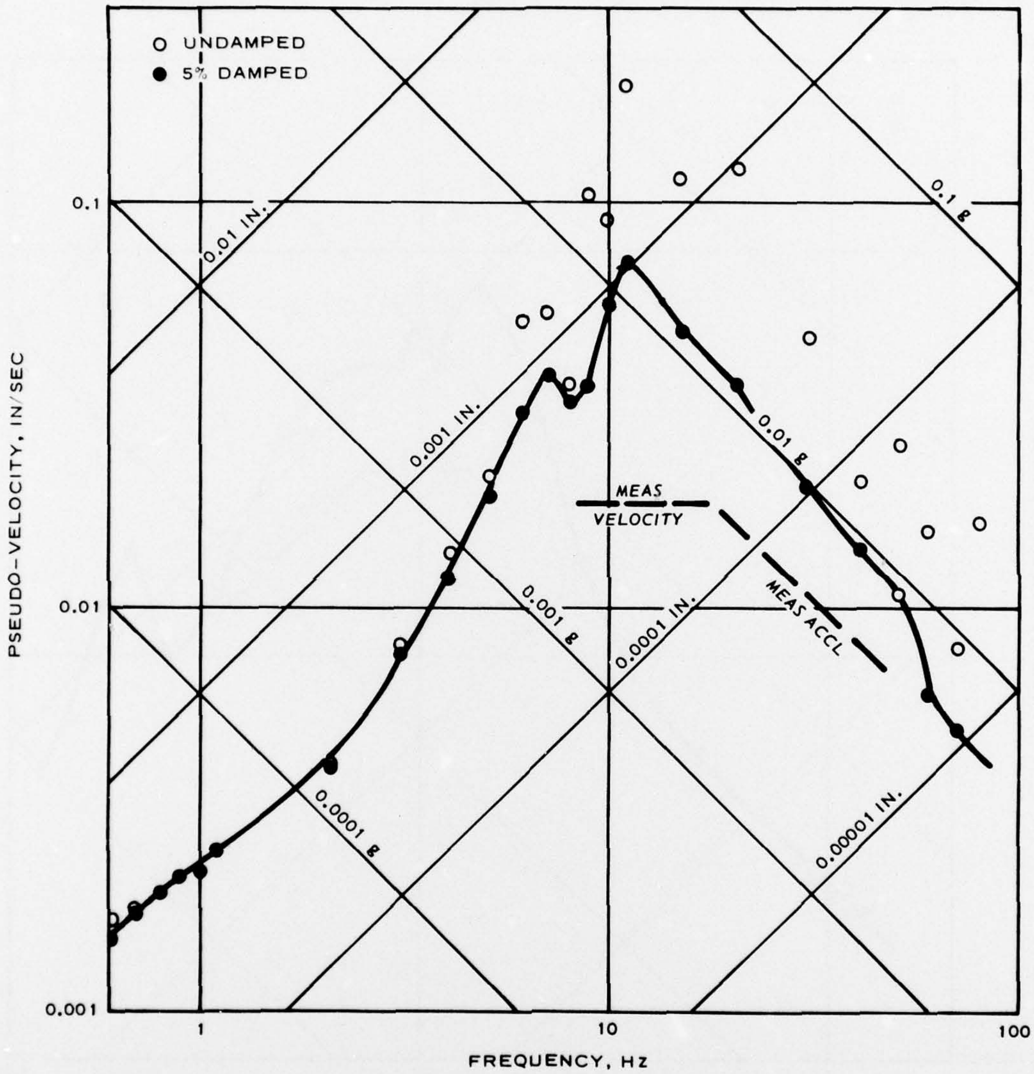


Figure 11. Undamped and five percent damped shock spectra for radial motion recorded on the ground floor of Building X-326 in shot 6

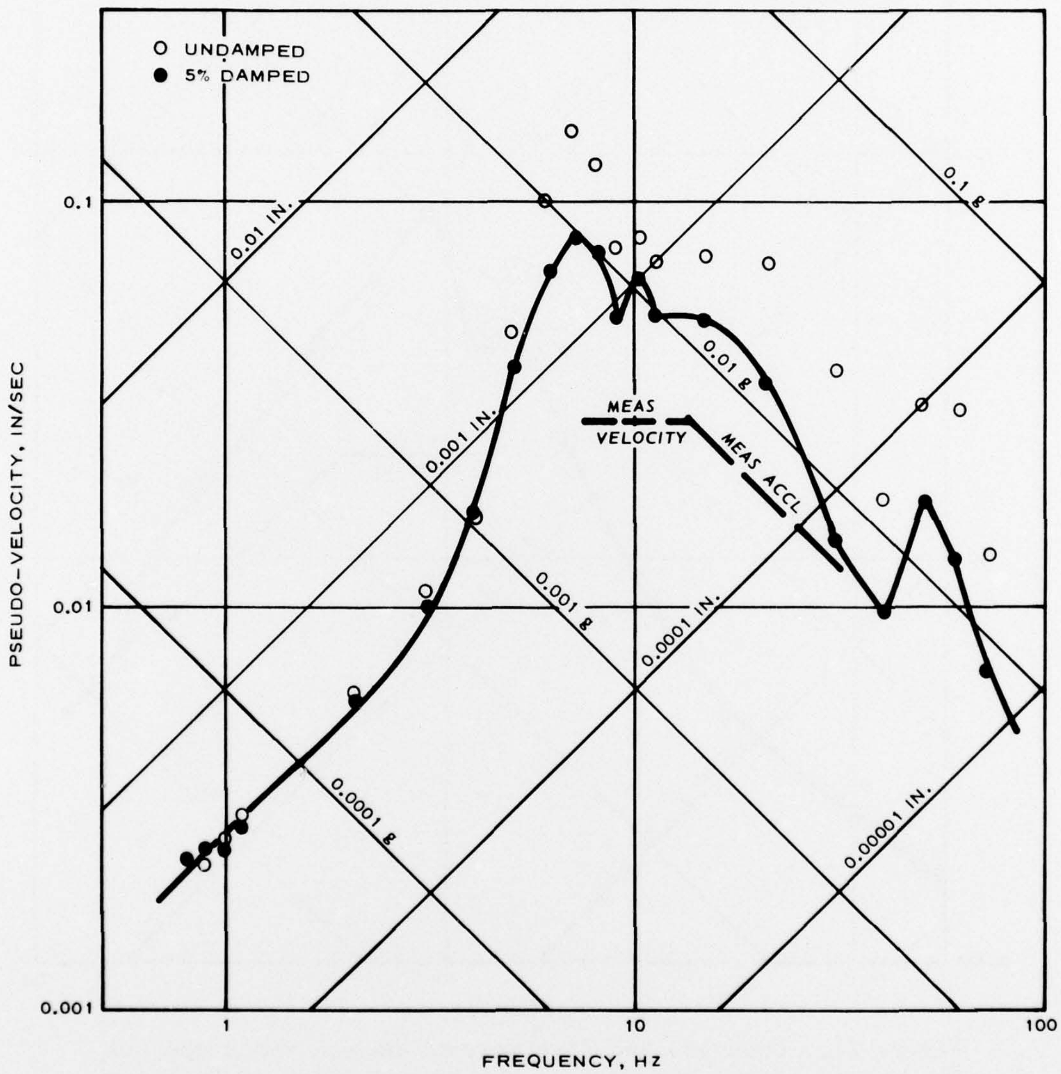


Figure 12. Undamped and five percent damped shock spectra for radial motion recorded on the second floor of Building X-100 in shot 6

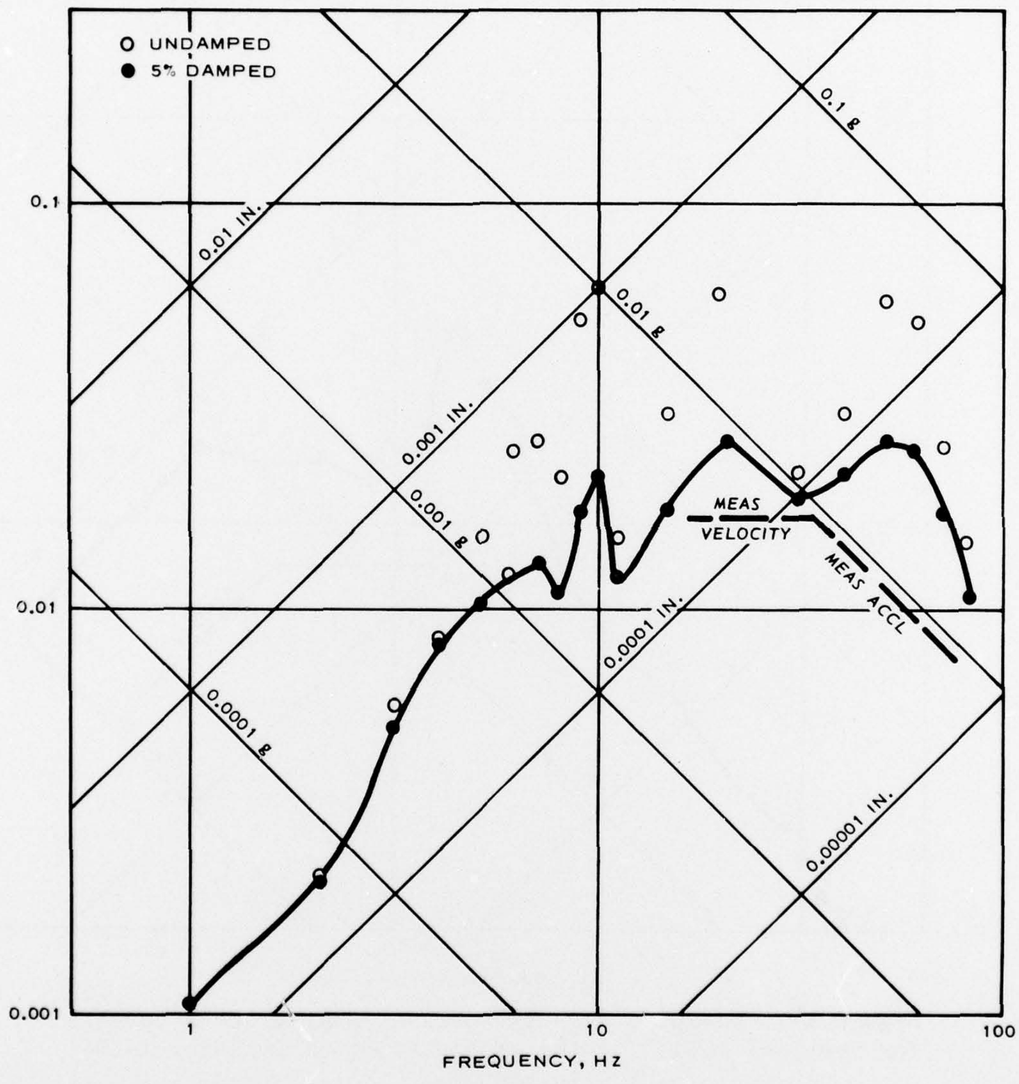


Figure 13. Undamped and five percent damped shock spectra for vertical motion recorded on the ground floor of Building X-326 in shot 6

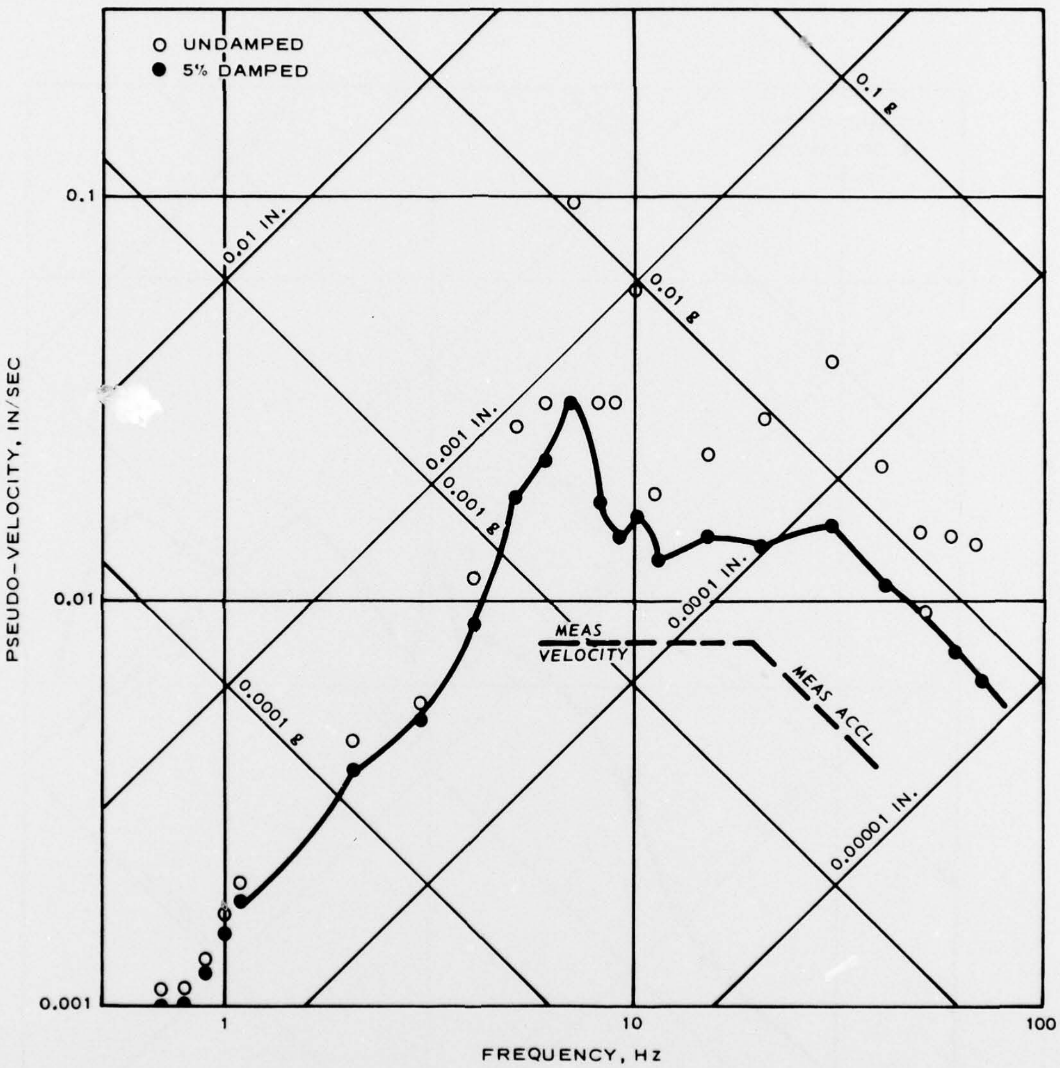


Figure 14. Undamped and five percent damped shock spectra for vertical motion on the ground floor of Building X-100 in shot 6

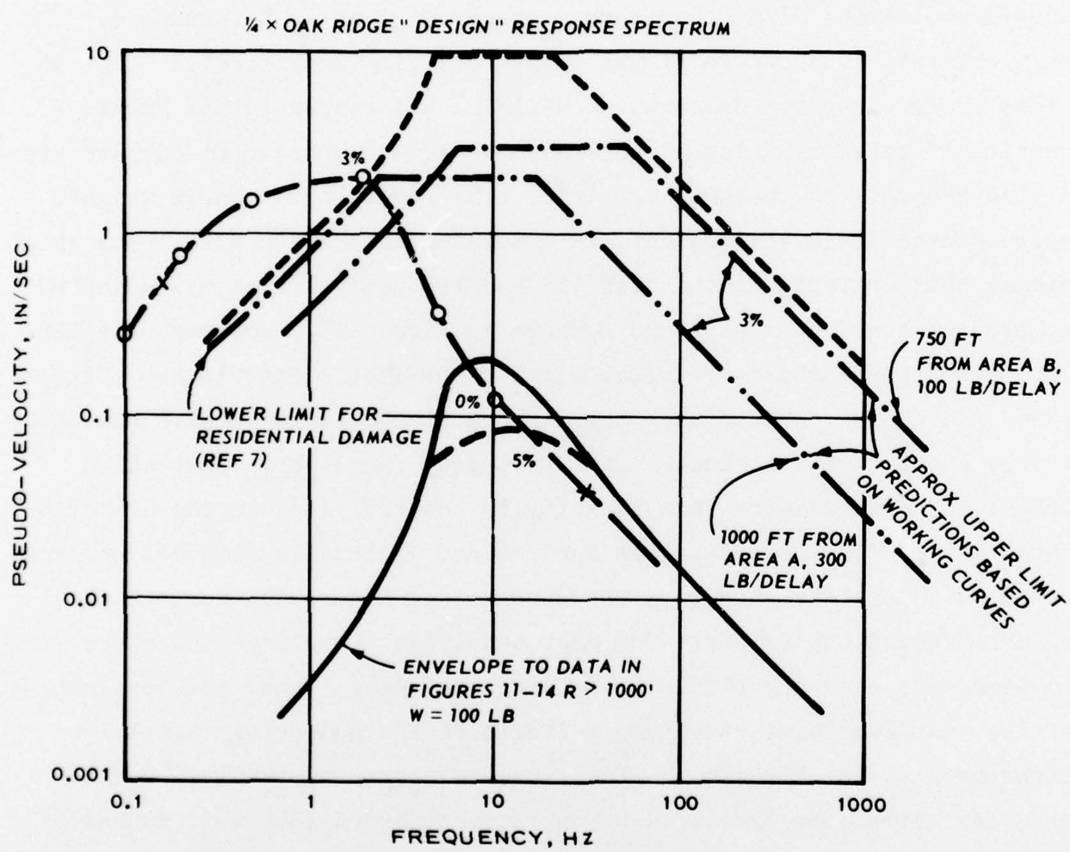


Figure 15. Comparison of data and predictions for recommended charge weights with safety criteria spectra

pseudo-velocity and pseudo-acceleration predictions shown. (4) The relative displacement bounds were obtained using an amplification factor of 2.5 and a displacement prediction equation given in Reference 7. Both predicted bounding spectra lie below the limits for residential structures given in Reference 7.

39. ERDA furnished a limiting shock criteria for "most-sensitive" structures.* It was in the form of a shock spectrum and as specified as one-fourth of the design earthquake spectrum given in Reference 9. The ERDA criteria is shown in Figure 15 where it is identified as "1/4 Oak Ridge Design Response Spectrum." While no structures in the "most-sensitive" category exist at this site it is of interest to compare predicted response to the ERDA criteria. The recommended charge weights will produce shock environments in moderately sensitive structures which exceed this criteria in the high (>5 Hz) frequency region as indicated by predictions for Areas A and B shown in Figure 15. However, the ERDA criteria appear arbitrary in the light of available experience. Structures and their contents have some inherent capacity to resist nonsteady state, short duration shock in the frequency range <u>above</u> that which occurs in earthquakes. This capacity is not reflected in the criteria noted above. The test data for shots 6 and 7 actually produced environments in moderately sensitive structures (see Figure 13, for example) which exceeded the criteria for most sensitive structures and there was no damage or even any hint of impending distress. Thus, the application of the most-sensitive structure criteria to the moderately sensitive structures at the Portsmouth plant appears ultraconservative, at frequencies above 5 Hz and it is strongly recommended that this course of action <u>not</u> be followed. Instead, it is recommended that the criteria of Reference 1 which were used in this study be adopted for the limit of blasting induced vibrations in moderately sensitive structures.

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* Baker, H. O., Letter to U. S. Army Engineer Waterways Experiment Station, ATTN: Mr. C. L. McAnear, dated 14 August 1975, U. S. Energy Research and Development Administration, Oak Ridge, TN, (see Drawing No. E-CV-42-446-C1-Rev 0, furnished as an inclosure to the letter.)

PART V: SUMMARY AND RECOMMENDATIONS

Summary

40. The charge limits for use in blasting operations at the Portsmouth Add-On Site, which will minimize public annoyance and prevent residential or industrial structure damage, are as follows:

Area	Type of Shot	Maximum Explosive per Delay* lb	Maximum Explosive per Round lb	Risk of Residential Damage	Risk of Moderately Sensitive Structure Damage	Most Sensitive Structure Criteria Satisfied?
A	Production	300	3000	1/2,500	<1/25,000	No
A	Presplitting	--	300	1/2,500	<1/25,000	No
B	Production	100	1500	1/2,500	<1/25,000	No
B	Presplitting	--	100	1/2,500	<1/25,000	No

* Delays of approximately 10 msec appear responsible in the light of the observed period of the motion.

41. The probability of internal component damage in the moderately sensitive structures cannot be accurately determined because the available response data are insufficient. If the risk to moderately sensitive structures stated above is unacceptable, then the Area B recommendations should be applied to both Areas A and B or the procedure outlined in paragraph 26 should be followed. Both of these procedures will reduce the risk significantly and in the latter, the maximum charge/delay is no larger than that already used in a test at the site.

Recommendations

42. It is recommended that competent mechanical engineers familiar with the internal components of the moderately sensitive structures at this site be queried as to their survivability in a shock environment whose spectra is represented by the dash-double dot line in Figure 15.

If they find that the risk of damage under this environment is acceptably small, the Area A charge limits listed above should be adopted. The Area B limits are controlled by residential structures limits, pose no threat to the moderately sensitive structures, and are recommended for adoption without qualification. Provisions should be made to (a) review the contractor's blasting plans before each shot, and (b) measure the ground motion at a location along the eastern fence line and near Building X-100 during the contractor's blasting operations as additional safety precautions.

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Table 1

Summary of Shots 1-9

Shot No.	Borehole* No.	Area	Total Weight of Explosives,** lb	Delays	No. of Channels of Free-Field Ground Motion Data	No. of Channels of Structure Motion Data	Observations
1	634	A	5	0	18	18	No motion was felt at Building X-100 or at Main Entrance Security Office
2	635	A	10	0	18	18	No motion was felt at Building X-100 or at Main Entrance Security Office
3	636	A	20	0	18	18	Motion was felt in Main Entrance Security Office
4	621	A	40	0	18	18	Motion was felt in Main Entrance Security Office and trailer outside Building X-100
5	644	A	60	0	18	18	Motion was felt in Main Entrance Security Office and Building X-100

(Continued)

* See location in Figure 1.
** Vibronite-S type explosive.

Table 1 (Concluded)

Shot No.	Borehole No.	Area	Total Weight of Explosives lb	Delays	No. of Channels of Free-Field Ground Motion Data	No. of Channels of Structure Motion Data	Observations
6	629, 637	A	100	0	18	18	Motion was felt in Main Entrance Security Office, Building X-100, and Building X-300
7	17A, 17B	A	50, 50	1 at 110 msec	18	18	Motion was felt in Main Entrance Security Office, Building X-100, and Building X-300
8	731	B	40	0	18	18	No motion was felt at Building X-100
9	737	B	61	0	18	18	No motion was felt at Building X-100

Table 2

In-Structure Motion Data

Shot No.	Total Charge lb	Building	Range ft	1st Floor Accel g	1st Floor Vel ips	2nd Foor Accel g	2nd Foor Vel ips	Remarks
				Building X-100				
5	60		1630	0.010	0.025	0.010	0.025	
6	100		1750	0.007	0.021	0.007	0.029	
7	100		1880	0.010	0.020	0.010	0.023	
9	61		3740	0.003	0.005	0.004	0.005	
Background velocity levels due to plant operations				--	0.002	--	0.002	
				Building X-326*				
5	60		2700	0.012	0.016	0.019	0.011	
6	100		2800	0.010	0.008	0.015	0.015	
7	100		2930	0.014	0.021	0.018	0.020	
9	61		4140	0.003	0.009	0.008	0.015	
Background velocity levels due to plant operations				--	0.003	--	0.009	
				Other Structures				
5	60	X-300*	2400	0.004	0.009	0.005	0.012	Background in X-300, roughly the same as shot effect
6	100	X-333*	3300	Below background levels due to facility operation				
7	100	X-633-2B*	3930	0.011	0.023	NA	NA	
9	61	X-710*	4100	0.003	0.023	0.005	0.052	
Background velocity levels due to plant operations								
		X-710*		--	0.001	--	0.001	
		X-633-2B*		--	0.002	--	0.001	
		X-333*		--	0.011	--	0.028	

* Moderately sensitive structures.